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WIND DRIFT ON LAKES

by

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Wind drift is the direct wind induced flow of a water surface. The wind also causes waves and hence a wave drift current, as well as sieches with their associated currents. Thus the movement of a float in the water surface is due to the combination of three things, the wind drift current, the wave drift current and the sieche or slope current. All these factors must be taken into account when we want to find a relation between wind drift and the wind causing it.

A knowledge of the wind speed and direction and its relationship with wind drift is of great importance. From it, one can anticipate movement of oil slick, floating debris and so on. A good example occurred during the recent strike of the workers at the sewage treatment works in Sydney. As a result of the strike, unprocessed sewage was poured into the sea and the wind blowing in the "wrong" direction caused the raw sewage to be deposited on the beaches causing a serious health hazard.

SOME THEORETICAL CONSIDERATIONS.

When wind blows over the surface of water, a tangential shear stress, τ_s, exists at the air-sea interface and air drags water along forming the wind drift (see Figure 1). Because of frictional effects between the different layers of water, the current gradually deepens. If we have a closed channel, wind causes a surface slope as well as a drift current away from the windward end in the upper layers of water. Consequently, along the bottom a return current exists which brings water back again to the windward end. A frictional shear stress, τ_b, is exerted by the lake bed on the bottom layers of water in opposition to this current. The two

stresses acting on the whole body of water, the wind stress on the surface and the friction stress on the bottom, act in the same direction and are balanced by the hydrostatic force due to the rise in the water level downwind. Thus, we have at a steady state, that is the wind blows for a long time and an equilibrium state is reached where the total water transport through a vertical section is zero,

$$\tau_s + \tau_b = \rho g \alpha H$$

where H is the mean depth of water, α is the slope of the surface along the direction of the wind, and ρ is the density of the water. If we let $\tau_b/\tau_s = m$ we find that the surface slope is

$$\alpha = \frac{(1+m)\tau_s}{\rho g H} .$$

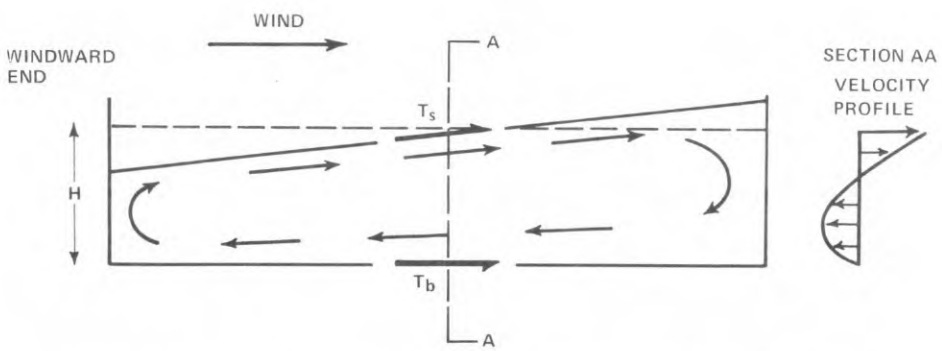

FIGURE 1 VERTICAL DOWNWIND CROSS SECTION OF AN IDEALISED LAKE ACTED ON BY A SURFACE WIND STRESS, Ts. A TYPICAL VELOCITY PROFILE IS SHOWN.

Keulegan (1951) assumed that the flow in the channel is a combination of a drift current at the surface caused by the wind and the gravity current at the bottom induced by the inclination of the upper free surface, its direction being opposite to that of the drift current. He derived the velocity profile for laminar type flow by neglecting inertial forces, supposing the flow to be steady, the pressure over the surface uniform and the surface displacements small with respect to the depth of water. The profile he obtained was parabolic in form with all particles between the surface and one third of the depth moving in the direction of the wind and the particles below this plane moving in the opposite

direction. (See Figures 1 and 2).

He also found that the value of m = 0.5 and the surface velocity V_w was given by

$$V_w = H\tau_s/4\mu$$

where μ is the dynamic viscosity of the water. This is an interesting result to note, as later when considering the analysis of the data obtained from the Coorong, V_w appears to be proportional to $\sqrt{\tau_s}$.

Based on Keulegan's work, Francis (1959) made the assumption that the forward drift occupies the top one-third of the depth of a lake and that the speed fell off parabolically in this layer. He computed the rise of the water level to be 0.05 feet in a 20 feet deep lake under the action of a 90 feet per second (53 knots) wind giving a surface drift of 3 feet per second.

This local rise in water level, though small, is directly connected with the wind drift. It is also indirectly connected with the sieche which develops when the wind suddenly stops blowing and the water starts oscillating about its mean position. This can be seen in a bowl of soup which has been tilted and suddenly levelled. The ends slosh up and down out of phase with each other and the horizontal current, as seen by the movement of the noodles, is greatest at the centre. In the middle of a lake the sieche current has its greatest effect.

When Coriolis force (due to the rotation of the earth) is not important, the wind drift is in the same direction as the wind stress. This is not so in the world's oceans. For example, in 1902 Nansen observed that the drift of ice-bergs did not follow the wind direction but deviated to the right by 20° to 40° when looking in the direction of the wind. He suggested that the effect of Coriolis force acting upon the moving water layers be taken into account as well as both friction between the wind and the sea surface, and friction within the different

layers. Ekman (1905) investigated the problem on Nansen's suggestion. Assuming turbulent flow in an infinitely deep ocean he obtained the theoretical result that, in the Northern Hemisphere the surface water moves in a direction that is 45° to the right and in the Southern Hemisphere 45° to the left, when looking in the direction towards which the wind is blowing.

If Coriolis force is unimportant, as happens in small lakes, we assume that the wind drift current V_w is a function of wind speed V_a and takes the direction of the wind if no obstructions are present.

THE WIND STRESS.

The fundamental relationship between the total wind stress, τ_s, at the air-sea interface and the wind speed, V_a, is not known with accuracy as the duration of wind action and the fetch are important parameters which need to be taken into account. However it is customary to express the wind stress at a given wind speed of the air over water in the form

$$\tau_s = \rho_a C(V_a) V_a^2$$

where ρ_a is the density of air and $C(V_a)$, itself a function of V_a, is the drag coefficient.

The value of the drag coefficient depends on wind duration and the fetch as well as the height over the sea surface where the wind is measured and it is still under discussion. Some take it as constant while others suggest an increase of $C(V_a)$ with wind speed and still others suggest decrease of $C(V_a)$ with increasing wind speed. De Leonibus (1966) has shown that $C(V_a)$ can behave in either way, depending on the Richardson number of the air flow over the waves. According to him $C(V_a)$ decreases with increasing wind speed for one range of Richardson numbers and increases with increasing wind speed for another range. A very useful compilation of the wind stress coefficient $C(V_a)$ determined by different methods has been given by Wilson (1960), who quoted 47 investigations. After having listed the different results, he arrived at

the conclusion that for strong winds (greater than 10 metres/second, mean about 20 metres/second) the mean value of $C(V_a)$ is 2.37×10^{-3} with a standard deviation of 0.56×10^{-3}. For light winds (less than 10 metres/second, mean about 5 metres/second) the scatter of $C(V_a)$ is particularly wide, the average value being 1.49×10^{-3} with a standard deviation of 0.83×10^{-3}. According to Wilson, $C(V_a)$ increases between light and strong winds from about 1.5 to 2.4×10^{-3} probably in a nonlinear manner and there is some reason to assume that for very high wind velocities some value in the neighbourhood of 2.4×10^{-3} will be approached asymptotically.

Keulegan has suggested that the surface wind stress may be divided into two parts, one part τ_1 associated with surface traction which produces the surface set up and the wind drift and another part τ_2 with the form resistance of the surface waves. We therefore have $\tau_s = \tau_1 + \tau_2$.

Fitzgerald and Mansfield (1965) have also suggested that

$$\tau_1 \propto V_a^2$$

so that the part of stress that gives surface slope and current is proportional to the square of the wind speed and

$$\tau_2 \propto V_a^3.$$

The latter part affects the wave form only. Thus we have

$$\tau_s = \tau_1 + \tau_2 = C(V_a)\, V_a^2$$

where $C(V_a) = A + B\, V_a$, A and B being constants.

EXPERIMENTAL WORK ON THE OCEANS.

Does the relationship $V_w \propto \tau_s$ imply that $V_w \propto V_a^2$, approximately? Uncertainty about the functional form of τ_s makes it difficult to carry out theoretical investigations. Most work done has therefore been semi-empirical or purely experimental.

Much work is done on the oceans using drift bottles and drift cards

but this gives only vague trends and nothing precise about wind drift. Many cards and bottles are never recovered. Bottles may be broken when they hit rocks or other hard objects. Also they might well perform several distinct journeys after a first stranding; they can be removed from the beach of first stranding by a particularly high-water level and start on a new journey. It could happen therefore that they might stay ashore for years in different places without being found and so making an estimate of drift speed quite worthless.

A good example is the discovery of a genuine distress message in a bottle in 1949. It had been released 45 years earlier by the polar explorer Baldwin. He had scribbled a hasty note calling for aid, had enclosed it in a small water-tight container and had cast it into the Arctic Ocean. The message drifted undiscovered for nearly half a century until a Soviet fisherman discovered it in the sea ice in the Russian Arctic. Although the message came to hand 45 years too late, the expedition did return safely and Baldwin died a natural death in 1933. In 1902-4, W.S. Bruce liberated a number of bottles to test the set and speed of the surface current in the Southern Ocean. Two were discovered in Victoria but at least one reached New Zealand and lay there for many years undiscovered amongst sand dunes three miles south of Rangitiki River in North Island. Heavy westerly gales which occurred sometime before September 1952, eroded the sand dunes and laid the bottle bare to view nearly 200 feet above the present high-water level.

Also many drift cards released together diverge rapidly because of two dominant ocean currents coming close together. Again we see that wind drift is not the only factor which determines float velocity. Therefore no attempts have been made to derive a law connecting the drift speed V_w with the wind speed V_a from data of this kind.

However, the study of bottle and envelope drift provides useful information for application to various problems to do with drifting oil slick, sea mines and so on. For instance there were hundreds of live

Japanese mines drifting about in the Pacific Ocean after World War II and it became imperative to know where and when such mines were likely to be encountered.

PREVIOUS EXPERIMENTAL WORK IN LABORATORIES.

More carefully controlled experiments have been done by some workers.

Keulegan (1951) using an experimental tank, found that the Reynolds Number

$$Re = V_w \rho H/\mu$$

could be plotted against the wind factor with the two equations

$$V_w/V_a = 7.6 \times 10^{-4} Re^{\frac{1}{2}},$$

$$V_w = 57.8 \times 10^{-8} (\rho H V_a^2)$$

where, as before, μ is the dynamic viscosity and H is the depth of water.

According to this investigation, at values of Re = 2000 the ratio becomes a constant so that $V_w = 0.033 V_a$, the surface velocity being independent of the depth of water in the tank. Van Dorn (1953) obtained somewhat similar results and found that the surface current appeared to be independent of wave action. Since then Longuet-Higgins (1953) has shown theoretically that there is in fact a very small effect, but so small it is negligible compared with the wind drift. Russell (1958) has verified Longuet-Higgins results experimentally.

Francis (1953) did some experimental work on the velocity distribution of the water in a channel using wind tunnels. He found that there is a definite similarity between the theoretical and measured velocity profile, as shown in Figure 2. For laminar flow the velocity decreases from the surface value V_w and reaches zero at a depth of H/3 as shown by Keulegan earlier. The velocity then increases in the opposite direction reaching a maximum at a depth of 2H/3 and after this going back to zero at the bottom of the tunnel. The measured profile is flatter than the theoretical near the bottom and this gives larger

velocity gradients there.

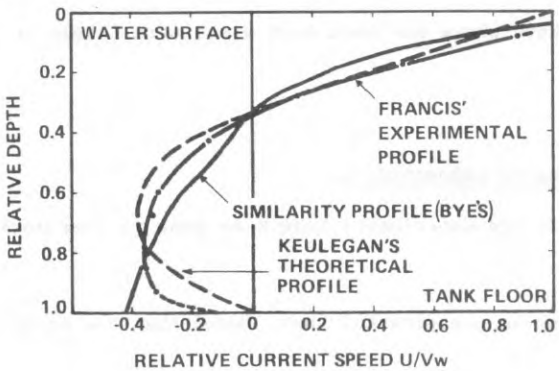

FIGURE 2 COMPARISON BETWEEN A THEORETICAL AND SOME MEASURED VELOCITY PROFILES.

The theoretical velocity profile found by Keulegan is no longer true when flow is not laminar. In practice flow often appears turbulent as is shown in the velocity profile given by Fitzgerald and Mansfield in Figure 3.

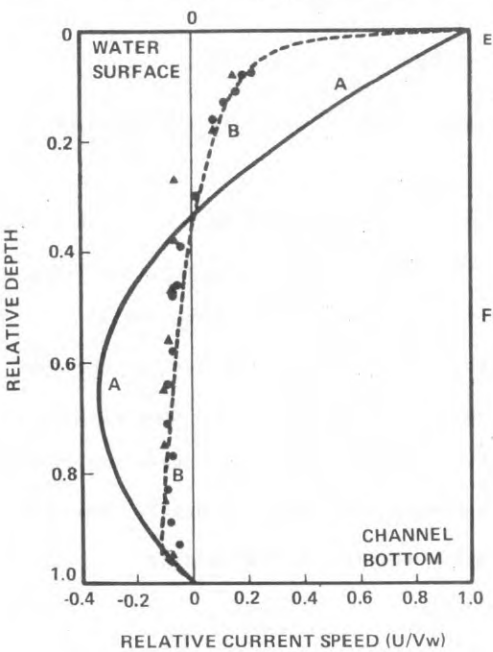

FIGURE 3 VELOCITY PROFILES ACCORDING TO FITZGERALD AND MANSFIELD. AA IS THE PROFILE ESTIMATED FOR THEIR REYNOLDS NUMBER $Re^* < 50$; BB IS THE ESTIMATE $Re^* = 1000$.

In turbulent flow, velocities decline beneath the water surface much more rapidly than in laminar flow. Because of zero total flow, the return velocities found towards the bed of the channel are reduced relatively.

PREVIOUS EXPERIMENTAL WORK IN LAKES.

We shall now consider Bye's work done on Lake Windemere (1965). His experiment involved the timing of drift floats of 2.5 × 2.5 cm.

cross section varying in length between 2.5 cm. and 1 metre, weighted at one end to float with their top just breaking the surface, and measuring the wind speed from a mast of sensitive cup anemometers.

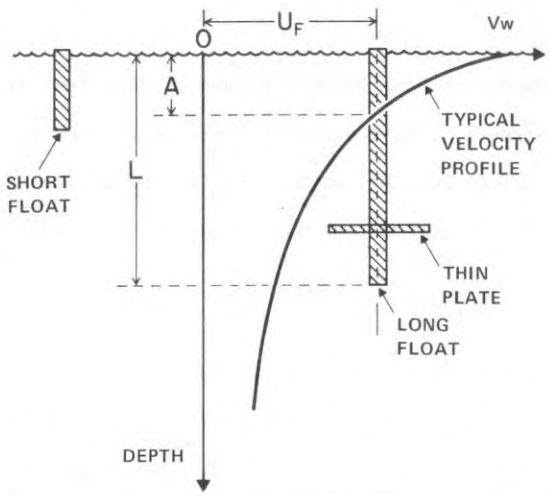

FIGURE 4 THE DRIFT FLOATS OF BYE.

Assuming that the velocity u of the current was logarithmic in form he found that the float would travel at the velocity it experiences at a depth of 0.2725 of its length below the surface i.e., A = 0.2725L. Thus, from the velocities of a series of floats of different lengths he deduced the current profile. The surface current was then estimated by superimposing the wind and current profiles which should match in velocity at the lake surface. The calculated surface currents were in close agreement with observations of Keulegan and Van Dorn.

A theoretical current profile, also deduced by Bye, is plotted with Francis' experimental profile in Figure 2. The agreement is fair except near the bottom. The bottom boundary conditions have been approximated here, that is the thin bottom layer in which the return current is reduced to zero is omitted.

Although the result of his experimental work was in close agreement with Keulegan and Van Dorn, Bye started by making the assumption that the theoretical velocity profile is logarithmic in form when calculating

the depth below the water surface at which the current speed equalled the float speed. Also he found the surface speed by extrapolating logarithmically. It is therefore no surprise to find that his experimental velocity profile ended by being logarithmic in form.

Some work with automatic reading current meters at different depths is being carried on at present to give velocity profiles. However, in all these cases the current speeds must be extrapolated to the surface to give the speed of the surface current and this is less accurate than direct measurement.

Haines and Bryson (1961) measured the surface drift directly and calculated the wind factor V_w/V_a on Lake Mendota. The surface drift is difficult to measure because of shifting levels with waves and many other factors which may affect it. The manual work thus becomes very tedious and much patience and perseverance are needed. Automatic reading instruments which measure current velocity have not yet been developed for use in this rapidly shifting thin surface layer. Haines and Bryson measured the current by the free drag method. Drags were made of two plates, 30 cm. by 10 cm., of light aluminium fitted together at right angles and attached to a 6 ounce milk can float. As said before the immediate wind stress is only one of several variables that will contribute to a water current at any time. Firstly, the sieche period which in Lake Mendota is 25.6 minutes must be taken into consideration. Thus the floats were allowed to travel a time of 25 or 26 minutes to integrate out the oscillating sieche current. The distance from drag release point to pick-up point was measured by means of a taffrail log. This instrument has a dial fastened to the side of the boat, and a length of rigid wire has two propellers attached. Motion through the water causes the propellers to turn and the number of propeller turns is registered on the dial. Within limits, the total turns recorded on the dial are independent of the speed of the boat and the instrument can measure the distance travelled through water. To nullify possible error, observations were made by coming down one side of the float and

going back on the other. The question which must be asked here is: "How accurately can this method measure the distance travelled by the float?"

The most interesting feature of Figure 5, which summarises their results, is the decrease in current above a critical wind speed about 5.6 metres per second.

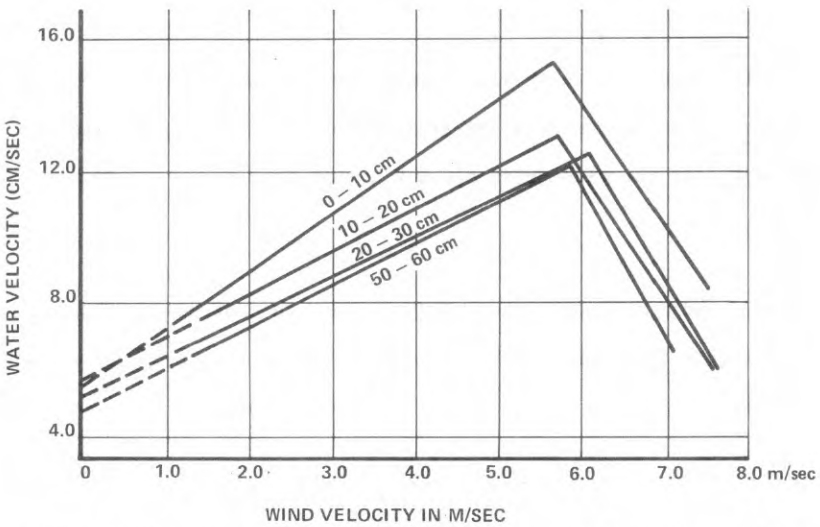

FIGURE 5 COMPOSITE LEAST SQUARE REGRESSION LINES OF WATER VELOCITY AS A FUNCTION OF WIND VELOCITY, AS FOUND BY HAINES AND BRYSON.

Regression lines were plotted for all water depths dividing the data into the wind speed ranges of 1-5.5 metres/second and 5.5-8.0 metres/second. These lines of best fit were obtained by standard least square methods in the form

$$V_w = a + b\,V_a$$

where below the critical wind speed b is the wind factor, eliminating a, the current that would exist in absence of wind. Thus they got the relation

$$\frac{V_w}{V_a} = \frac{5.3}{V_a} + 0.013.$$

The overall value of wind factor in the first 60 centimetres of water was 0.013 which is somewhat less than the figure accepted by most authors in the literature. Above the critical wind speed the average wind factor was given by

$$\frac{V_w}{V_a} = \frac{38.0}{V_a} - 0.042.$$

Of course, water velocities cannot continue to decrease with increasing wind speed. Perhaps the wind factor at higher values follow a non-linear instead of a linear pattern. Empirical confirmation will have to await more observations taken at higher wind speeds.

The results of both experiments done in lakes, that of Bye and of Haines and Bryson, show a linear relationship existing between the wind speed V_a and the wind drift speed V_w, that is

$$V_w = \alpha + \beta V_a$$

where α and β are constants. This appears to contradict Keulegan's theoretical findings that the wind drift speed is proportional to the surface wind stress which is approximately related to the square of the wind speed. His own experiments gave

$$V_w = 0.033 V_a$$

for Reynolds number 2000. Close examination of his theoretical work shows that he actually found

$$\frac{V_w}{V_a} = 7.6 \times 10^{-4} \left(\frac{V_w \rho H}{\mu}\right)^{\frac{1}{2}}$$

so that, in fact,

$$V_w \propto V_a^2$$

and

$$\frac{V_w}{V_a} = 0.033$$

only when the Reynolds number $\left(\frac{V_w \rho H}{\mu}\right)$ is equal to 2000.

THE COORONG EXPERIMENT.

In conjunction with a series of experiments about wind effects on water levels (Noye, 1967) some experiments on wind drift were carried out in the Coorong of South Australia in December 1967. On a small island in Stony Well Basin a field station was set up which measured

wind speed and direction at a height of two metres, barometric pressure, water level and wave heights.

Nearby, in water approximately 0.7 metres deep where the Coorong had a level sandy bottom, the speed of drift of 3 cm. square floats 3 mm. thick, was measured. A small buoy attached to a pole by a cord 10 metres in length marked out the distance to be covered by the floats and indicated the direction of travel. A float was placed on the surface of the water far enough upstream of the pole that it had reached a steady speed when it drifted past the pole, and the time taken for the float to drift from the pole to the buoy was measured by stopwatch. From this the float speed was calculated. The readings were rejected and the experiment was repeated if any small waves present, broke and trapped the float in their "white cap". Meteorological and water level measurements were recorded at the same time as the drift measurements, viz. every ten minutes, for a continuous period of 84 hours.

The measured speed, f, of the float may be considered as due to the drift speed of the surface layer of the water combined with any wave drift and slope current which existed at the same time. Longuet-Higgins and Russell have shown that the speed of the wave drift is several orders of magnitude less than the wind drift for small waves of period 1 - 2 sec. and amplitude 2 - 3 cm. encountered during the experiments. The contribution of the wave drift toward the float speed was, therefore, neglected. Assuming, for wind drift V_w, a relation of the form

$$V_w = \beta V_a,$$

and for the slope current u a relation

$$u = \alpha + \gamma(d\zeta/dt),$$

where ζ is the water level recorded and α, β, γ are constants, we have for the total drift speed, which is the speed f of the float,

$$f = \alpha + \beta V_a + \gamma(d\zeta/dt).$$

Using the values of f, V_a and ζ recorded every ten minutes, regression analysis can be used to find "best" values, in the sense of minimizing the sum of squared errors, for α, β and γ.

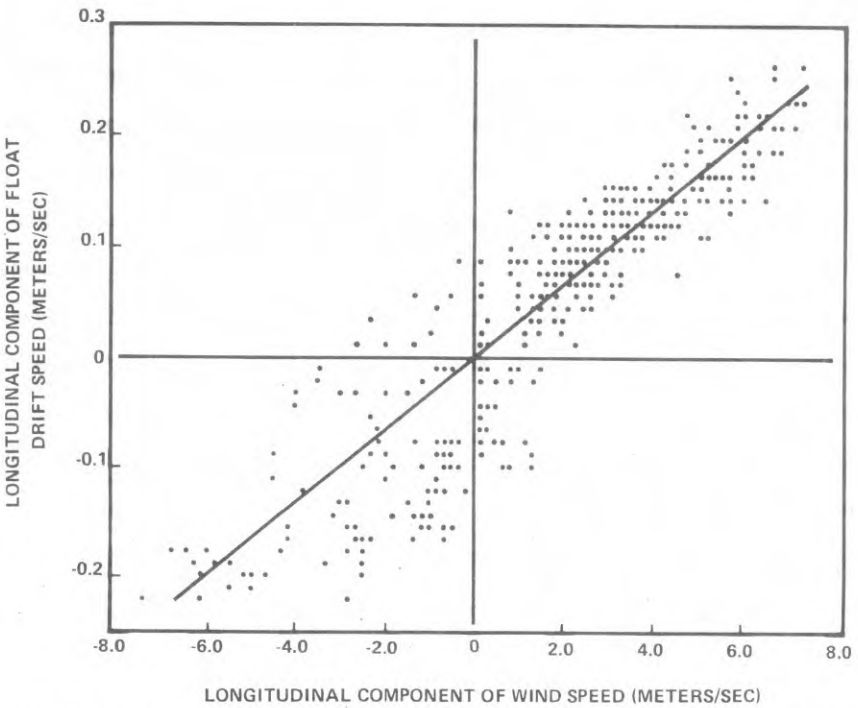

FIGURE 6 SCATTERGRAM AND LINE OF BEST FIT FOR LONGITUDINAL COMPONENT OF FLOAT DRIFT SPEED PLOTTED AGAINST LONGITUDINAL COMPONENT OF WIND SPEED.

Figure 6 is a scattergram of the longitudinal component of float speed plotted against the longitudinal component of wind speed. Longitudinal components of the speeds were taken along the axes of the Coorong, since it is an elongated body of water and slope currents are directed along its length. With the directions of the wind and of the float drift being essentially the same, the value of the wind factor is the value of β found by fitting the data to the relationship described above.

The line of best fit shown in Figure 6 was obtained assuming no slope current existed, so $\gamma = 0$, when

$$f = 0.002 + 0.032\ V_a$$

with $R^2 = 80.9$ where R^2 is a percentage indicating goodness of fit, and

which is 100 when all the data lie on the line.

$$R^2 = \sum(\hat{f}_i - \bar{f})^2 / \sum(f_i - \bar{f})^2$$

where $\hat{f}_i$ is the value predicted by the formula found, f_i is the observed value and $\bar{f}$ is the mean value of the float drift speed. Including the effect of a slope current in the relationship the data gave

$$f = 0.003 + 0.032\ V_a + 0.001(d\zeta/dt),$$

with $R^2 = 82.55$, indicating that a better fit to the data had been found. From this relation, the value of the slope current,

$$u = 0.003 + 0.001(d\zeta/dt),$$

is of the order of 0.5 cm/sec. which is much smaller than the wind drift speed which is of the order of 20cm/sec. The wind drift speed, V_w, is therefore

$$V_w = 0.032\ V_a$$

with the wind speed, V_a, measured at a height of 2 metres.

This result is similar to the one Keulegan obtained from his wind tunnel experiments, viz. a wind factor value of 0.033. His wind speed, however, was measured closer to the water surface. Haines and Bryson found the value of 0.013 for the wind factor on Lake Mendota. This is difficult to relate to the above values for two reasons: firstly, their current speed was an average over the top 60 cm. of the water which is less than the surface drift speed, V_w, and secondly, their wind speed was taken at a height of 5 to 5.5 metres where the reading is greater than it is closer to the surface of the water. Both these factors lead to a decrease in the value of the wind factor, V_w/V_a, which undoubtedly explains their apparent low value.

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STORM SURGES

by

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When violent storms such as cyclones move from the ocean across the coast, the sea level rises above the normal tide level. Part of this is due to the rise in the sea surface which is simply a static effect of the low barometric pressure, but much is due to either the dynamic effect of the moving low pressure system associated with the storm, or to the wind set up. The wind set up, sometimes called the wind tide, is caused by winds dragging surface water into a semi-enclosed sea or to a shoreline and physically piling it up there.

The term "surge" is used to describe any transient motion of part of a body of water, although a surge may consist of more than one variation in the surface. Several mechanisms are known to cause surges; a landslide falling into a lake may cause one, underwater earthquakes may cause them, cyclones moving over relatively shallow water cause surges.

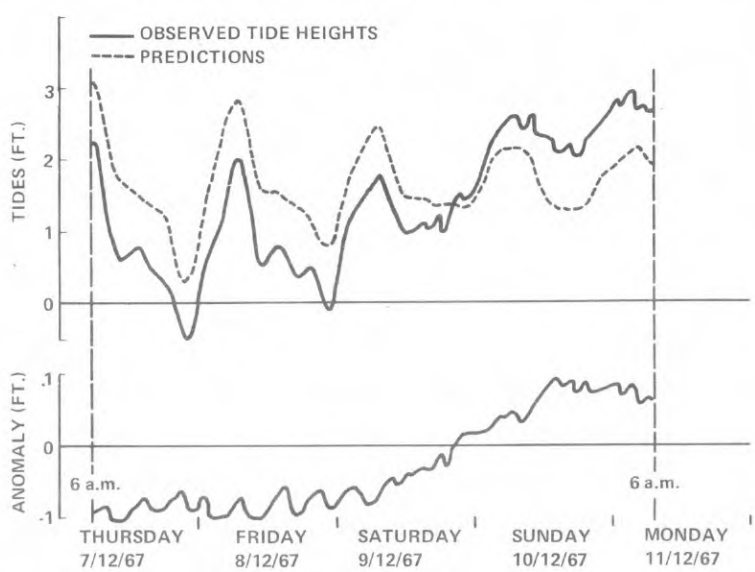

FIGURE 1 PREDICTED AND RECORDED TIDE WITH THE TIDAL ANOMALY, VICTOR HARBOR 7–11 DECEMBER 1967

A typical case of a meteorological or storm surge is shown in Figure 1. From 8-10 December 1967 the mean sea level at Victor Harbor on the coast of South Australia rose from over one foot below the expected level to a value nearly one foot above this level. The part of the tide which is due to the gravitational effects of the moon and the sun is referred to as the astronomical tide. Because these astronomical forces repeat themselves regularly this part of the tide can be predicted with great accuracy — this is the tide which is listed in tide tables. In 1967 Noye and Easton wrote a program for use on the University of Adelaide's computer which calculated tidal constants from tide records, that is the amplitudes and phases of the tidal constituents at each of the periods of the astronomical forces. One month later Noye and Kautsky developed another program to predict the time and height of the tidal extremes using these tidal constants. Since that time these computer programs have been used to produce tide tables for Australian ports for the use of the Royal Australian Navy.

By way of contrast, the part of the tide due to meteorological effects and sometimes called the meteorological tide can be a high proportion of the total tide, but cannot be predicted more than a few days ahead. In the example given for Victor Harbor the predicted astronomical tide has been subtracted from the total tide to give the tidal anomaly or surge which in the main is a meteorological effect. It can be seen that the range of the surge is of the order of 2 feet, nearly as great as the range of the astronomical tide which was about 3 feet during that time.

Surges may occur in lakes or small seas as well as in the open oceans. On June 26, 1954, a severe squall line with an abrupt pressure jump (a pressure change of about 1 inch of water occurred in a few minutes) moved across Lake Michigan at a speed of nearly 70 miles per hour. This is close to the speed at which a free wave travels over the surface of that lake, so a condition close to resonance prevailed. Surges 3 to 6 feet high were recorded at Michigan City and surges 3 to 8 feet high were observed at Chicago about an hour later. Seven people were drowned as a result (see

SURGES IN THE NORTH SEA

The low lying countries bordering the North Sea are subject to severe storm surges which cause inundation of coastal regions, extensive damage and very often loss of life. It has been estimated by Peters (1954) that 100,000 lives were lost in England and the Netherlands in three storm surges which occurred in 1099, 1421 and 1446. More recently, during the storm surge of January 31 - February 1, 1953, nearly 1800 people were drowned in the Netherlands when seawater flooded about 800,000 acres of agricultural land and damaged 47,300 houses, 9215 of them being beyond repair. In the same storm more than 300 lives were lost in England and over 160,000 acres of land were flooded.

The gale that caused this surge was probably the most severe to occur over the western and central North Sea in the last few centuries. It entered the North Sea between Scotland and Norway and moved in a south easterly

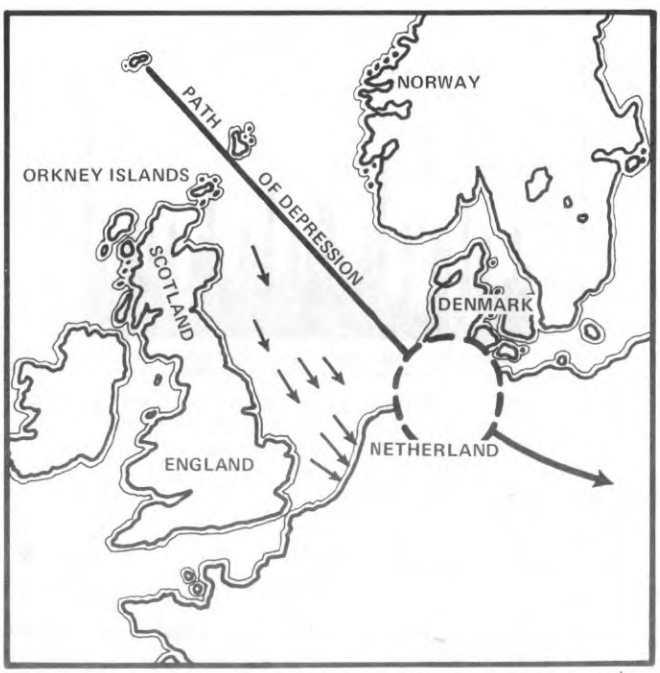

FIGURE 2 TRACK OF THE LOW PRESSURE SYSTEM AND POSITION OF THE STORM CENTRE AT THE MOMENT OF DISASTER IN THE NETHERLANDS 1 FEBRUARY 1953

direction until it struck the Netherlands early in the morning of February 1. (see Figure 2.) The lowest pressure recorded was 970 millibars in the Orkney Islands where wind gusts up to 125 miles per hour were recorded some 5 hours after the low had passed.

The highest waters, and the greatest damage, occurred in the Netherlands. Fortunately, the maximum storm surge did not coincide with the maximum astronomical tide. Farquharson (1954) states that he has found this to be true for all previous North Sea surges; it is not known whether this is fortuitous or whether there is some physical reason for it. The maximum annual storm levels at Hook of Holland are shown in Figure 3. Prior to this storm level which was nearly 13 feet above the normal level the previous maximum recorded storm level was less than 11 feet above the normal, 50 years earlier, in 1894. It has been calculated that the probability that a surge of the same magnitude as the one in 1953 occurs, is only once in about 400 years.

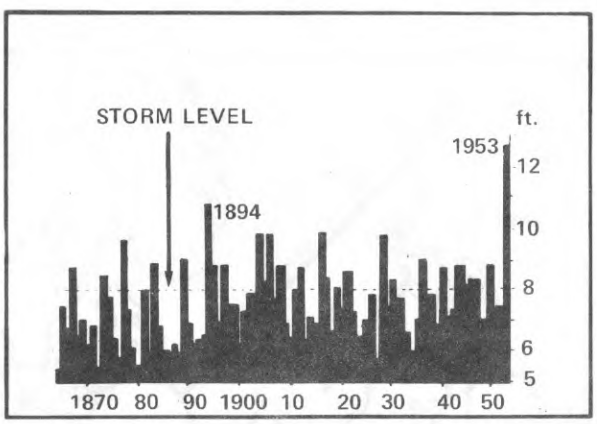

FIGURE 3 MAXIMUM ANNUAL STORM LEVELS AT HOOK OF HOLLAND DURING THE PAST CENTURY

METEOROLOGICAL CAUSES OF SURGING

There are two meteorological factors which may cause a build-up of mean sea level which temporarily raises the mean tide level without necessarily altering the shape and amplitude of the astronomical tidal curve. These factors are the atmospheric pressure and the wind.

Considered statically changing atmospheric pressures cause relatively deep seas, which are connected to the oceans, to behave like an inverted water barometer. Increasing barometric pressures will lower sea level while falling pressures will raise it, the alteration of sea level being about 1.1 feet for a pressure change of 1 inch of mercury. As 2 inches of mercury is about the maximum deviation of the barometric pressure from the normal figure of 29.8 inches, the maximum elevation or depression of sea level from this cause can be expected to be little more than 2 feet. If p is the corrected barometric pressure in inches of mercury, then the elevation h_s feet of sea level, assuming the pressure systems are stationary, is given by

$$h_s = 1.1\ (29.8 - p).$$

Therefore the elevation of the sea surface would be nearly 1.7 feet at a point where the barometer stands at 28.3 inches.

However, the influence of the changing pressure on the generation of a surge is also related to the speed of movement of the pressure change. When the pressure disturbance moves with a critical speed, which is the speed of travel of a free long wave on the surface of the sea, it will generate a greater surge than if the speed is above or below this value. This is an example of the phenomenon called resonance. Slow changes of barometric pressure will not generate very large surges; these are associated with reasonably fast-moving storm conditions.

If frictional forces are neglected Proudman, as early as 1929, showed that the elevation, h_d feet, of sea level at any place resulting from a moving pressure system is related to the elevation, h_s, for the corresponding stationary system, by the formula

$$h_d = \frac{h_s}{1 - K^2/68D}$$

where K is the speed in knots of the pressure system and D is the mean depth of the sea, in fathoms. If a low pressure system is travelling at 50 knots over a sea 50 fathoms deep then at a given point where the barometer reading is 28.3 inches, the elevation of the sea surface would be 3.8 times the

static effect which is h_s = 1.7 feet. The actual elevation is therefore h_d = 6.4 feet. It is clear that the movement of the pressure system must be included in any calculations if we want a good indication of its effect on the sea level.

The formula given neglects frictional forces. When the pressure disturbance has the same speed as a free surface wave on water of depth D fathoms, so that $K = 8.2\sqrt{D}$ knots, a resonant situation exists. The denominator in the formula then becomes zero and the sea level elevation is infinitely large, which is most unrealistic. However, the use of the expression does indicate conditions likely to lead to very large elevations or depressions in the sea surface.

The wind effect may be of two types. The wind may actually increase or reduce the quantity of water in a partly enclosed sea and it can also cause the surface to tilt. During 31 January/1 February 1953 the level of the whole North Sea was increased by the gale force winds from the North-West driving water into the sea from the ocean outside. Rossiter has calculated that about 15 trillion cubic feet of water entered the North Sea between Scotland and Norway during the 9 hours between 9p.m. on 31 January and noon on 1 February. This caused an increase of over 2 feet in the level of the whole North Sea during this period.

Strong winds blowing from one direction for a prolonged length of time can also physically "pile up" water on the shore or move it off shore. In the case of an enclosed sea the result is to give a slight tilt to the whole sea surface. This effect is particularly noticeable along shorelines of estuaries and semi-enclosed seas such as in the Gulf of Carpentaria. In the case of a wind blowing with a speed of V knots for a considerable length of time (12-24 hours) across an enclosed sea of width L miles and average depth D fathoms, the increase in depth on the leeward side is approximately h_w feet where

$$h_w = \frac{LV^2}{10000D}.$$

A 50 knot wind blowing for most of one day across a sea of 80 miles width and mean depth 10 fathoms piles up water to an additional depth of 2 feet on the leeward side, while the level falls by the same amount on the windward side.

It is clear that the set up, h_w, is inversely proportional to the depth D. Hence the wind effect increases with decreasing depth. The Gulf of Carpentaria and Gulf St. Vincent are both very shallow and this effect is very pronounced.

A similar effect applies if the wind blows across the continental shelf at the boundary of an open ocean. The effect is small for a narrow shelf such as near Port MacDonnell, as the shelf width, L, is only of the order of 15 miles at this point, but it is large for wide shelves such as the one in the Great Australian Bight. The edge of the continental shelf is close to the 100 fathom line which is marked on Figure 5. Large wind effects are evident in the tide records from Thevenard where the shelf width, L, is of the order of 150 miles.

STORM SURGES IN THE GULF OF CARPENTARIA

The Gulf of Carpentaria (see Figure 4) seems particularly susceptible to tidal effects of meteorological origins. Positive storm surges, in which the observed tide is greater than the astronomical or "predicted" tide, are generally associated with tropical storms and several cases of the order of 20 feet are on record. These are amongst the largest recorded in the world.

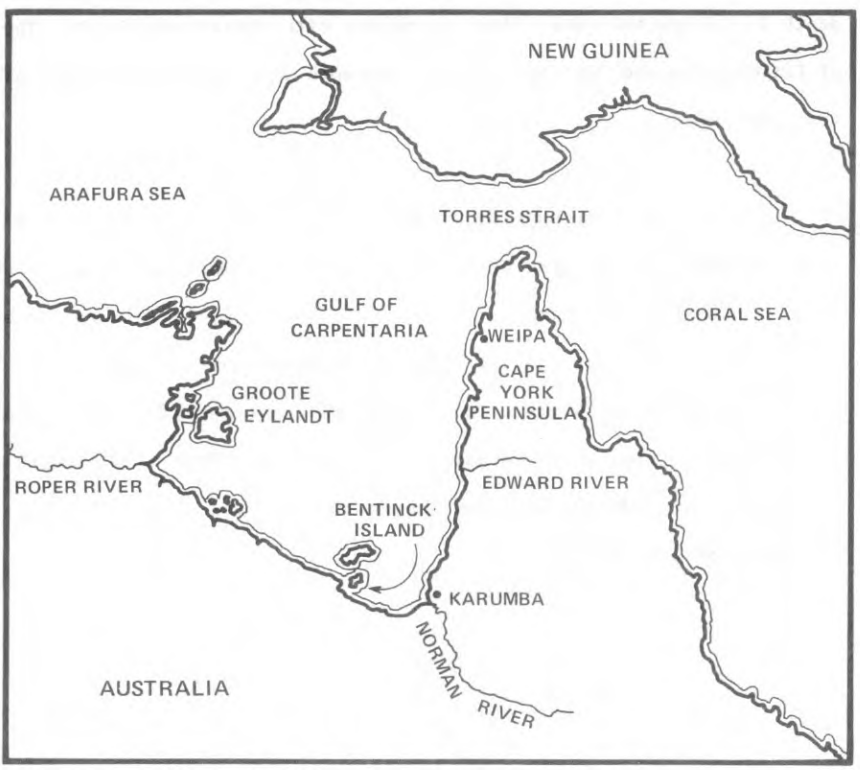

FIGURE 4 THE GULF OF CARPENTARIA

For example, in March 1923 a severe tropical cyclone crossed Cape Yorke Peninsula and developed to full hurricane intensity over the Gulf (see Whittingham, 1968). The "Douglas Mawson" a ship of 333 tons, encountered the hurricane near Weipa and was lost with all hands. The storm then moved across the Gulf to Groote Eylandt where it produced a spectacular surge of

23 feet above mean tide level. Water levels were raised about 9 feet above High Water all along the southern Gulf shores from the Norman River to the Roper.

Again, in February 1964 cyclone "Dora" crossed the Peninsula near Edward River Mission, where the sea came right over the beach ridge, a rise of approximately 18 feet. A Geodetic Survey party found that the beach ridge top was 15 feet above low water level, and the water mark left by the tide on a beacon standing on the ridge was at least 2 feet above the ridge top. The sea water extended beyond the beach ridge a distance of nearly one quarter of a mile inland.

At one time, a 12 feet surge at Bentinck Island in the South Eastern gulf region forced the Kaiadelt people of the island to abandon their homes (see Tindale, 1961) while the highest tides at Karumba have reached 22 feet (see Whitehouse, 1944).

Negative surges, in which the observed tide is lower than the expected tide, are much smaller, but are of great navigational significance particularly in connection with the river ports on the western and southern shores of the Gulf. An interesting and protracted negative surge occurred at Karumba in August 1957. Daily mean levels for the 13th. through to the 20th. were; 5.8, 3.3, 1.2, 1.6, 2.7, 3.7, 4.9, 5.3 feet above gauge datum.

The great storm surges of the Gulf of Carpentaria are caused by a combination of effects, particularly by surface tilt due to wind effects and by dynamic pressure effects. The Gulf tides are important in the study of these surges for two reasons. Firstly, if a surge is superimposed on Spring Tides at the time of high water it will inundate more country. Secondly, there is the effect of tidal currents; winds opposing an ebbing current will hold back much of the water and the sea will remain near the high water level for a much longer period of time.

STORM SURGES ON THE COAST OF SOUTH AUSTRALIA

Although the southern coast of Australia is subject to severe storms, especially in winter, storm surges have not previously been studied for this region. The only available information appears in an internal publication of the South Australian Harbors Board (1964) in which recorded maximum and minimum tidal extremes are compared with their predicted levels and date of occurrence. For instance, on August 14, 1934, the recorded high tide at Thevenard (see map in Figure 5) was 10.7 feet compared with the predicted figure of 5.2 feet, a positive surge of 5.5 feet; on 24th March, 1939, the minimum tide reading was -1.2 feet which was 1.6 feet below the predicted value of 0.4 feet. However, the greatest deviations did not necessarily occur at the tidal extremes; the values available are merely good indicators of expected surges. Along the Great Australian Bight surges of the order of 3 feet have been recorded at most of the ocean ports while in the bays near Thevenard they may reach 6 feet. A caution in the South Australian Tide Tables states that for Thevenard "Easterly winds lower sea level by 1 foot to 2 feet, and low waters at spring tides often fall below datum in such

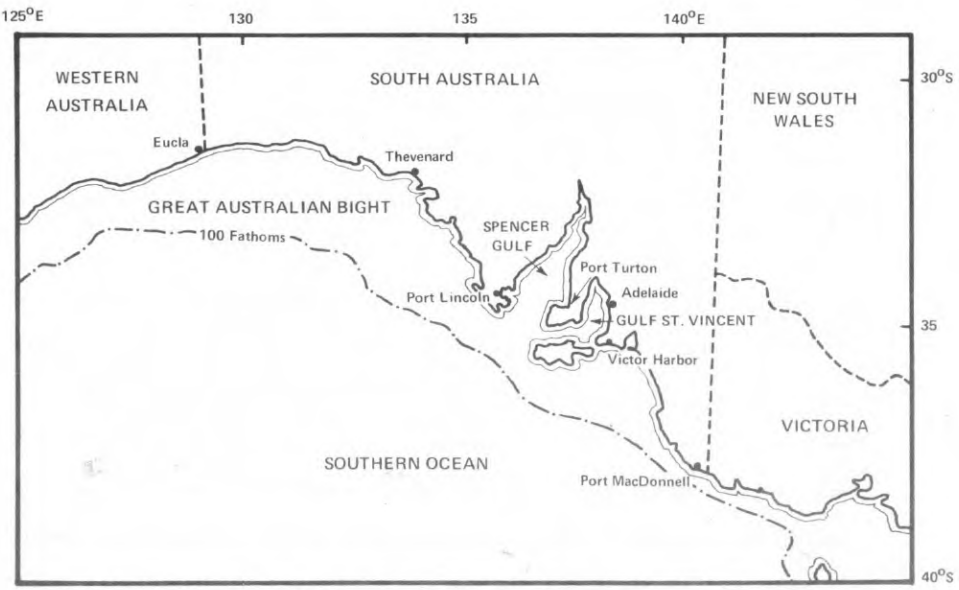

FIGURE 5 THE SOUTHERN COAST OF AUSTRALIA

conditions".

An interesting surge occurred between 13th and 15th September 1967 (see Figure 6). An increase in tide height of nearly 2 feet was recorded at Thevenard early in the morning of the 14th while an increase in water level of 2.5 feet was recorded at Victor Harbor late that night. Smaller surges were recorded at Eucla, Port Lincoln and Port MacDonnell. It is of interest to note that this surge occurred at neap tide when the tidal range of 2.2 feet at Victor Harbor was less than the increase in sea level caused by the surge.

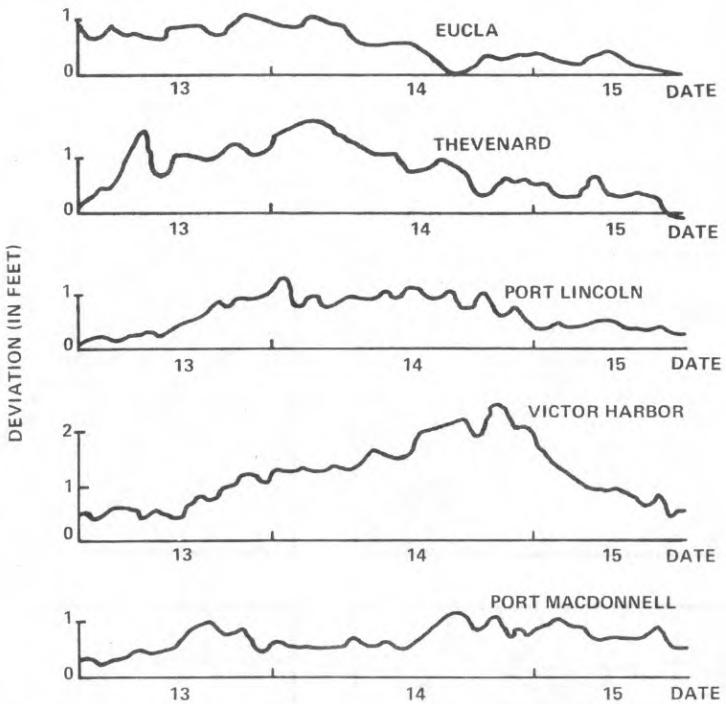

FIGURE 6 THE POSITIVE SEA LEVEL SURGE ALONG THE COAST OF SOUTH AUSTRALIA, 13–15 SEPTEMBER 1967

The changing weather system which caused these surges is shown in Figure 7. At 3p.m. on 12 September, a low pressure region lay south of the Great Australian Bight. A high had moved across South Australia in the previous 24 hours and the barometric pressure in Adelaide was 30.17 inches and falling. The maximum coastal wind speed was 5 knots. At 3p.m. the next

day an intense low pressure region was situated just south of Kangaroo Island. A cold front was moving eastward across the Bight and the coastal winds were increasing in intensity. The barometric pressure in Adelaide was 29.83 inches and it was still falling. By 3p.m. on the 14th September the low was just south of Port MacDonnell. The winds were very strong, being of the order of 15 knots over the Bight and up to 30 knots over the Gulf system. The atmospheric pressure in Adelaide had fallen to 29.78 inches. It would appear that the strong southerly winds were the main cause of the large positive surges at Thevenard and Victor Harbor on this day. The next day the winds had died away completely and the atmospheric pressure in Adelaide had risen to 29.97 inches.

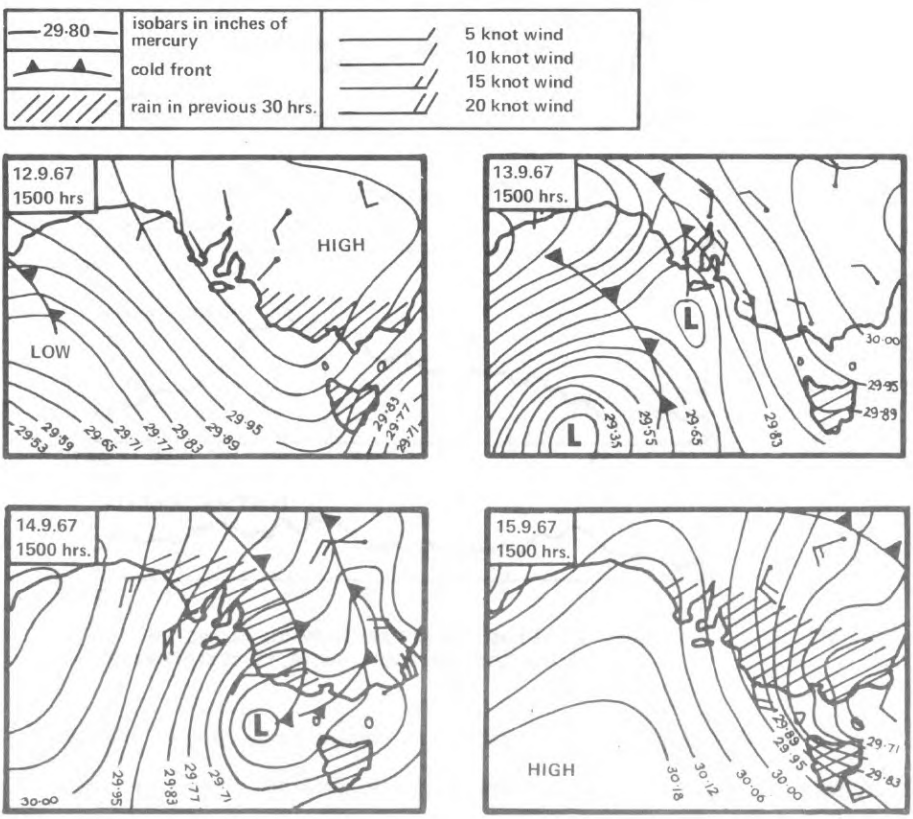

FIGURE 7 THE WEATHER SYSTEM OVER THE SOUTHERN OCEAN 13–15 SEPTEMBER 1967

WEATHER EFFECTS ON THE S.A. GULF SYSTEM

The only documented information about meteorological effects on the waters in Spencer's Gulf and the Gulf of St. Vincent appears in the South Australian Tide Tables issued each year. Based on many years of experience with the effect of changing atmospheric pressure and winds blowing with different speeds from various points of the compass, the following note has been written:

"Although the predictions are computed by accurate methods, it must be borne in mind that exact agreement of the predicted with the actual time and height is unusual, since the variable effects of wind and atmospheric pressure cannot be predicted, especially for a locality like Port Adelaide, where the meteorological effects may bear a large proportion of the ordinary tide; nevertheless the predictions will be near enough for all practical purposes.

The following remarks will be of service in estimating the meteorological effect upon the tides:— Sea level rises as the barometer falls, and vice versa, about 1 in. for every 1/20in. of the mercury. The wind also produces a considerable effect upon the tides, especially upon the height, but it is difficult to give any general rule for the effect. An easterly wind is generally accompanied with a high, and a westerly wind with a low barometer, so that as far as height of the tide is concerned the wind and barometer act in the same direction. The effect is that with easterly wind and high barometer the tides are a little earlier and the water lower. Westerly winds and low barometer have an opposite effect.

The shape of the two gulfs and Investigator Strait also contribute to the wind effects. At Port Adelaide N.W. winds cause the highest tides, raising sea level up to 4ft. above normal, while continuous S.E. winds depress it as much as $1\frac{1}{2}$ft.

In the northern part of Spencer Gulf the most marked weather effects on

the tide occur with the passage of a deep depression across the Southern Ocean, on a track from Cape Leeuwin to Tasmania. With the onset of northerly winds, as the barometer starts falling, the tides are below prediction; but as the wind backs to N.W. an increase in level occurs, with a gradual build-up if the wind remains steady. A strong gusty N.W. wind, with such a depression, backing to W.S.W. at about the time of low water, will cause a storm surge of maximum amplitude, and heights may be expected from 2ft. to 5ft. above prediction. These high levels will continue until the wind backs and the barometer starts to rise; but unless the depression's passage is blocked the wind usually backs rapidly to S.S.E. within 12 hours, and with a rapidly rising glass the tides return to normal (or below) in about that time."

Until the present time no one has scientifically investigated the effects of winds and moving pressure systems on the waters in our Gulf system. Work on this has been started at the University of Adelaide by Noye and Tronson. A computer program has been developed to calculate the response of the sea level at any place in either Gulf under the influence of different ocean tides and weather conditions. The depth at more than 1000 points in the Gulfs has been used in mathematical equations which describe the motion of the sea surface and the mean speed of the currents at each of these places. These equations are solved for any given tidal conditions at the entrances to the Gulfs and for any given wind speeds and atmospheric pressures over the sea surface. This is done at equally spaced intervals of time, say every five minutes, so that the complete response of the waters of the Gulfs at any time and any place can be found with great accuracy.

An initial investigation, in which a steady South wind of 20 knots was suddenly imposed on the normal tide, has shown the way in which the level of the water in the Gulf changes with the passage of time. Some unexpected features were evident, such as a three hourly oscillation in the computed sea level recorded for Port Turton, which is in a rather sheltered part of Spencer's Gulf (see Figure 5). Within two hours of the onset of the wind,

sea level at this point had fallen by 3 feet and then began to oscillate with a three hour period about a mean sea level which was 2 feet below the normal water level. The initial range of this oscillation was 2.5 feet. After 12 hours the range of this oscillation was reduced to 1.5 feet, and its mean level was only six inches below normal.

This program can also be used to compute the frequency response of the astronomical tide at any point within the Gulfs, relative to the tide at Port Adelaide. With this frequency response the astronomical tide at that point can be calculated at any time knowing only the tide at Port Adelaide. At present harbour engineers must instal tide gauges and collect and analyse many months of records before knowing the nature of the tide at each location being considered for a harbour. An investigation using the system described will indicate the suitability of any possible harbour site in the two Gulfs in a few minutes of computer time.

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* Now the South Australian Department of Marine and Harbors.

METEOROLOGICAL SATELLITES

Talk by G. T. Rutherford to A. M. A. Adelaide, 4th June, 1971

There are two main difficulties which confront the Australian meteorologist. First the complexity of the subject (a universal problem) so that even with a perfect set of weather observations, accurate forecasts could not always be achieved. Secondly, a handicap particularly applicable to Australia and the southern hemisphere - a lack of adequate data. It is this topic that is discussed here.

The south Indian Ocean west of Australia is an area of major importance for forecasts for the southern states. It is an area conspicuous for its lack of data. Weather reports are available from only a few islands and from shipping and aircraft. Over most of the ten million square miles nothing is available.

So at least was the story until the advent of the meteorological satellite during the last decade opened up new and exciting prospects for meteorology. The first United States meteorological satellite (TIROS 1) was launched in April, 1960 - a device similar in size and shape to a hat-box, weight 250 lbs, orbiting in 90 minutes at about 500 miles altitude at 5 miles per second. Its chief component, a TV camera providing at regular intervals pictures about 1200 miles along a side and revealing cloud panoramas never before observed.

The cloud pictures clearly showed arrangement of clouds in significant patterns, covering a wide spectrum of both sizes and shapes. Cloud spirals indicated low pressure systems at various stages of development; cloud bands for fronts; streaks and shadows indicated high level jet streams; the tightly coiled cloud bands of a tropical cyclone; the spectacular inverted "comma" pattern a warning of a newly developing system.

Satellites launched by the U. S. A. since 1964 have been equipped with the Automatic Picture Transmission system (APT). This has been a major advance since pictures can now be read out by any station with inexpensive equipment instead of the former massive read-out complex located in Alaska, U. S. A. Australia has now three such stations at Melbourne, Perth and Darwin and satellite data is available to meteorologists a matter of minutes after the satellite observation.

An almost equally important technological advance has been the development of sensors by which the satellite obtains information while passing at night over the dark side of the earth. Unlike the TV camera, which operates in the visible band, these sensors respond to radiation in the infra-red and other channels. The radiations are emitted from various surfaces, i.e. land, sea or cloud and these surfaces are distinguishable from the satellite at night as well as by day.

The radiation measurements are electronically transmitted by APT and appear in "photo" format similar to the visible TV data.

About 30 orbiting satellites have been launched by U.S.A. since TIROS 1 in 1960. All satellites of the TIROS and NIMBUS series have been experimental satellites controlled by NASA (National Aeronautical and Space Administration, U.S.A.). Satellites in the ESSA, ITOS and NOAA series have been operational satellites controlled by the national U.S. weather service (recently under the National Oceanographic and Atmospheric Administration - NOAA). The U.S.S.R. have also a series of orbiting satellites from which meteorological data is available but to date without a local APT-type read-out facility.

A new step forward in meteorology will soon be made from the development of the stationary as opposed to the orbiting satellite described earlier. The stationary satellite, so-called because it is stationary relative to the earth, is one launched to a height of 22,400 miles above the equator. At this height it completes each orbit about the earth in the same time as the earth's period of rotation, viz 24 hours. A satellite so launched will, therefore, appear stationary to an observer on earth. Such satellites are already in orbit for communication purposes. A particular use is the TV relay of important events in the other hemisphere.

The stationary satellite represents an area of vast meteorological potential not yet exploited. A capability exists for continuous watch of any meteorologically suspicious area such as the Australian Bight for new disturbances, the Coral Sea for tropical cyclones. A zoom lens-type facility may "blow up" such areas for close examination. The stationary meteorological satellite is likely also to have an interrogatory facility to obtain data from remote automatic weather stations and a meteorological communication facility to exchange weather material with other countries.

The U.S.A. plan to establish a GOES (Geostationary Operational Environmental Satellite) in 1972 over the Pacific Ocean. The Japanese are planning a Japanese-type GOES over Australian longitudes about 1976. This latter, in particular could be of inestimable value for Australian meteorology.

Meteorology still awaits a means of obtaining quantitative data from satellites as distinct from present data which requires subjective interpretation. Recent experimental data obtained by NIMBUS using SIRS (Satellite Infra-Red Spectrometer) suggest progress in this field.

A time will come when data will be available which is adequate in quantity and accurate in quality. Add to this improved computer methods of preparing forecast charts. A logical follow on is accurate computer forecasts of the weather elements themselves.

ONCE-IN-A-LIFETIME FLOODS AT ARKAROOLA

by

Reg. Sprigg

Arkaroola Pty. Ltd. Adelaide

March 5th, 1971 witnessed cyclonic floods of unprecedented intensity at the new Arkaroola Sanctuary and Tourist Resort.

To Arkaroola, a 1600 million year old geological paradise, nestled away in spectacular granite mountain country in the Northern Flinders Ranges, disruption is scarcely something new. Crustal upheavals with their attendant earthquakes have torn great geological faults that all but span the continent through this area. Mobile granite plugs and enormous outpourings of basaltic lavas in ancient times have set this mountain province apart as a giant museum all but unique in Australia. More recently, relentless forces have lifted the ancient plateaus of the Freeling Heights to more than 3000 feet above the now fossil sea beds of Cretaceous times. These latter preserve the remains of extinct dinosaurs and giant shell-encased relatives of the squids that dominated these great inland seas of less than 100 million years ago. Hot Springs now flow from great fault fixtures that earlier facilitated the subdivision of ancient low lands into mountains and near-sea-level playa lakes that in turn became the cemetery of the swamp dwelling Diprotodons of only "yesterday".

All of this seems a far cry from the droughts and flooding rains that dominate the colourful semi-desert that makes this colourful region what it is today.

Two-and-a-half years of extreme drought, aggregating little better than five inches of useless light rain, gave way on March 5th, 1971 to cyclonic rains on a scale that have rarely come to these parched areas in the history of white man.

The first hint we at Arkaroola had of things to come, was a warning out of the blue by a tribal elder of the Andjamutanas, Mr. Wally Coulthard who foretold of big rains pending. Aboriginal chief, Clem Coulthard, further explained that these would not be ordinary rains, but exceptional floods. We grinned our disbelief.

Arkaroola's rains for 1971 came on the last weekend of February. A total of 132 points were recorded at Arkaroola Village. Not enough to break the drought, but at least there was no damage - parched soil soaked up every drop that fell with scarcely a gutter running.

The Coulthards were not put off. The big rains were just ahead. We remained sceptical. In only August last year we had witnessed Clem perform the Andjamutana rain dance at a night picnic for

Premier Dunstan and other guests at Echo Camp. All that an incredulous party got from the incantation was a sudden eerie, but minute-long, wind storm in an otherwise calm night that scattered coals, papers and guests alike. "A wonderful piece of stage management" commented Premier Dunstan, and Chief Coulthard only laughed.

But March 1971 was to be something quite different. Saturday 5th was to be the Royal Victorian Aero Club's big 30 plane fly-in. From Moorabbin everything had been readied. A big resort staff was tensed to cater for every need. An impressive list of mountain tours, including visits to the Paraluna Hot Springs and the numerous impressive water holes had all been carefully scheduled. There was nothing left undone. A memorable fly-in was all but guaranteed.

Only three days before the Fly-in date, hostess Griselda had decided to apply for insurance cover in case of marring rains. Four days prior notice was the requested minimum. It was now too late. A great cyclonic rain depression lying over the Gulf of Carpentaria since March 1st couldn't be expected to influence the weather so far south. How wrong could the amateur weather watchers be?

When a party of us took off for Arkaroola on Friday afternoon in order to precede the Moorabbin Flyers, the first apprehension was made manifest as our Cessna entered an unusual cloud build-up along the north-eastern fringe of the Flinders Ranges. It mustn't rain, and it can't, we assured ourselves. That was March 4th.

Saturday morning dawned brightly enough, but the bank of clouds was still there. There had also been some light over-night drizzle. None of us now felt completely happy, the more so as Wally Coulthard had again gone on record to say that a really big one was on the way - one of the biggest ever.

In the back of some of our minds was the knowledge that an intense but unnamed cyclonic depression had remained stationary over the Gulf of Carpentaria for five days now - just soaking up tropical sea moisture rather like a formless visitor from space. Unknown to us great cyclonic spiral tentacles were in fact at that moment groping southward across the continent.

Come Saturday noon, the clouds darkened and their base finally closed down over the local mountain tops. Light drizzle settled in, and the scenario for one of nature's most spectacular dramas had been inexorably set. Two planes scampered in from Moorabbin, Victoria, via Broken Hill, New South Wales. Our hearts sank. They only just made it. High level moisture had facilitated the build up of water-laden clouds to 38,000 feet they reported. The heavens were beginning to open, and the great deluge of 1971 had already begun.

Twenty eight plane-loads of flying revellers, replete with all that goes with a chop picnic in Broken Hill, were already in disarray and variously making their decisions to abandon the Arkaroola Fly-in and scamper back to Broken Hill or Melbourne - whichever they could.

And did it rain? Three inches of drought-quenching water soaked into the ground overnight. Deep disappointment for the Arkaroola Village staff - but elation for distraught and drought-impoverished pastoralists.

The Sunday morning radio was quickly alive with reports of record rains. Seven inches on Muloowatana and still raining. South-western Queensland and northwestern New South Wales were already awash with flood waters. People were being marooned on roof tops, animals trapped, and river levels rising seemingly everywhere.

Outside we could no longer see a mountain peak. The rains poured down but still only the tributary creeks ran. Later the rain eased. Relieved, and in the belief that our three inches was all but soaking completely away, we drove to Arkaroola Waterhole in the great Arkaroola Gorge. Only moderate stream floods had to be negotiated and the waterhole had only just filled and a gentle stream now extended half a mile beyond. Merciful Powers above! No damage, just drought quenching rain.

For the next two or three days it rained enough to add to the points rain score by half an inch or so each day. Still no damage, but creeks flowing nicely. The much publicised prayers of the Longreach pastoralists over the last few Sundays had been answered very satisfactorily.

And then it happened.

On Thursday afternoon several of us had taken to checking well and pump installations within a mile or so of the village, obstructions were cleared and we marvelled at the minimal damage caused to roads and constructions generally. Wywhyana Creek adjacent to the Village motel area was flowing broadly but only two feet deep. A delightful sight indeed.

At 3 o'clock the heavens literally opened. For more than an hour it teemed. Two inches and finally three inches deluges in one mighty display of "cloud burst". Griselda Hill - a spectacular quartzite "hogback" rising sheer out of the east bank of Wywhyana Creek became a series of never-to-be-forgotten cascades. Cameras clicked and movies whirred, nature was recorded in its most extreme mood. Waterfalls erupted from nowhere and leaped into space. At the same time Wywhyana Creek became a roaring torrent. Although the village is set 50 feet above creek bed level, fears were being canvassed that the rising rivers might not know where to stop. The valleys began to fill.

Now it became evident why our camels which normally staunchly avoid hanging around the village, had taken such firm decision to become semi-permanent residents of our piece of alluvial high ground. They had steadfastly refused to leave the immediate village vicinity for almost a week now, and their decision now made sense. Camels take extreme dislike to getting their feet wet, and they showed absolutely no intention of being caught up in the swollen rivers now.

By Sunday morning Arkaroola Station Homestead had had 968 points and the Arkaroola Village 1020 - making the total score almost one foot of rain in the last two weeks.

On the more human level, the floods brought widespread problems. Everywhere, it seemed, people, animals and property were marooned. The Moomba-Gidgealpa oil and gas fields were isolated. Numerous road parties were in trouble on the Strezelecki track. Soon police spotting planes were overhead. Our guests firstly had gone through depression at being unable to return to work and the city rat race. No one had been endangered - merely inconvenienced. Fancy dress evenings and other divertissements soon made the "ordeal" a party in itself.

Finally, came the mopping up and the assessment of damage. Roads were quite impassable only yards from the Village. Exoil's T.D. 20 Bulldozer settled gently in silt five feet deep while extricating the Arkaroola grader from its own bog. It was now one pulling out the other as man and machine battled to open the roads for the first trickle of traffic. North Flinders Mining Company threw in another bulldozer, and that bogged and debogged its way into clearing an opening to the Station and finally to the airfield.

After two more days the first escape became a reality. There was a new reluctance to leave, but a spectacular cloud build up over the Gammon Ranges, late on Sunday 14th, only five miles to the south, cut the romancing. One inch of rain fell on nearby Balcanoona Station within an hour as the runways were being checked carefully - only drops fell on Arkaroola's shale surfaced strip. The three planes were away within minutes of each other - and the staff of Arkaroola and the Mining Companies were left to a gigantic clean-up. The most pressing problems of all remained, namely the opening of the mail road to Balcanoona and Leigh Creek. This was top priority in every-one's reckoning.

Remarkably, by a series of local diversions, the High-ways Department had an emergency road open in only two or three days. Within a week much of the more obvious repair was a matter of history. But of the private roads within Arkaroola - almost 100 miles of new development - the job was to be more painful. Magnificently the Exoil and North Flinders Mining Companies rallied to the task in their own

and the joint interest. By Easter time the main scars had been removed, and access via what is Australia's most spectacular mountain road - the Ridge Top Track was open to four wheel drive tour vehicles along much of the length.

All that remained was to see and understand what had happened weatherwise. Estimate put the total volume of water dumped by the decaying cyclonic rain depression on to the east Central Australian continent, as being in the vicinity of 1000 million acre feet, a mere 160 odd thousand billion gallons.

No wonder Lake Frome all-but filled, and Lake Eyre covered later as the Great Cooper and Diamentina Rivers flooded into the continent's remotest sub-sea level depression.

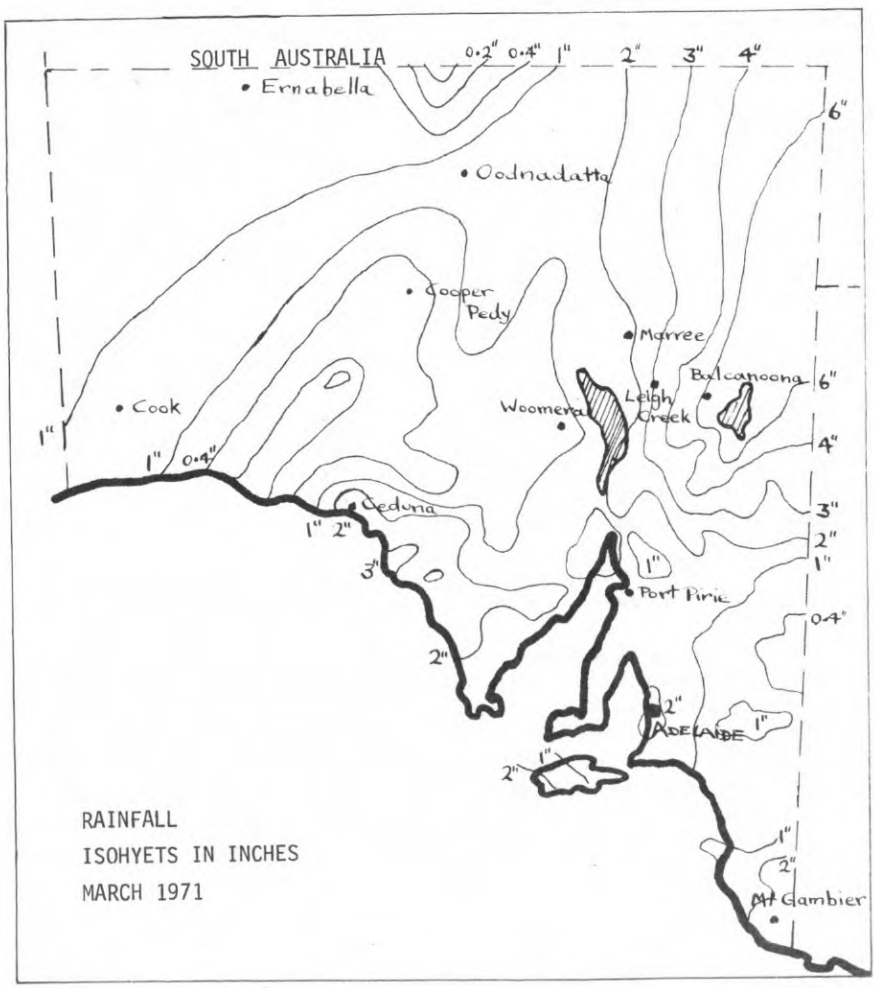
Meteorologically what did happen? The satellite weather pictures for the week preceding and the week during the flood rains give the story very clearly.

The cyclonic disturbance over the remote Gulf of Carpentaria was a thirsty one. At first apparently weaker than cyclones "Aggie" and "Fiona", which preceded it in early February, the depression never did receive a code name. After settling almost stationary over the Gulf for almost five days the system literally sucked up thousands of billions of gallons of water as it hungrily stored up energy finally to exceed that of a myriad of atomic bombs. Great spiral arms blanketed the 400 miles wide Gulf and finally caressed the land. Almost as if by command - and only aboriginal mystical insight appears to have forecast it - the great cyclonic rain depression of 1971 turned south and quickly moved wholly onto the continent. Remarkably the cyclone retained its spiral form and whirled southward finally expanding to more than 1000 miles in diameter, and unleashing its moist load in a watery fury that dwarfed imagination. Meteorologists quickly pointed out that it is rare for a cyclone to preserve its "eye" so perfectly in its passage so far into the centre of the continent. This it did, almost to Innamincka.

Just what happened subsequently at Arkaroola and the north-eastern edge of the Flinders Ranges is more readily explicable.

The most southerly spiral arms of the cyclone repeatedly swept up over and across the great mountain escarpment that demarks the eastern region of the North Flinders Ranges. Driving northwesterly the steep topographic gradients forced the saturated air to rise rapidly and in so doing cooled and condensed the cloud moisture into larger drops finally to disgorge and deluge the country intensely. A marked rainshadow to the west resulted in only 3.5 inches on the adjoining Yudnamutana Station compared with Arkaroola Village's 10 inches and Muloowatana's 15 inches.

Weather men can only thank modern technology of the satellite era for an almost hour by hour surveillance of the cyclone's development through growth, maturity and decay. It is now clear that 1971 has already recorded the most intense tropical cyclone activity since 1955. Weather men can also commit to their computer models one of the more remarkable cyclonic floods experienced in modern history. It is only a pity that more records of atmospheric pressure within the "eye" of the system could not have been recorded in the formative days in order to categorize the system fully. That unnamed cyclone of early March 1971 brought the Andjamutana's prediction true but failed to achieve a code name.



THE NATURE AND ORIGIN OF AUSTRALIAN DESERTS

by

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Modern deserts occupy narrow belts which straddle the tropics of Cancer and Capricorn. They lie particularly in the lee of mountain ranges, or deep in the interior of continents. Prevailing winds are very dry, usually having precipitated moisture before they reach these parched areas.

Deserts tend to be stretches of desolate sand dunes, sprinkled with dry lakes and stunted vegetation. Mesa "flat tops", tent hills, and resistent inselbergs usually inhabit these places like lone sentinels.

Despite forbidding appearances, these large desert areas (some eight million square miles in all) represent the world's largest land banks. One day this potential will be turned green by irrigation as exploding human populations force man to purify sea and saline waters for this purpose.

A characteristic of most deserts is high summer day heat. The deserts of southern Patagonia, however, are more the result of high winds and low rainfall. By comparison, in typical tropical belt deserts low humidity and clear skies let the sun's rays penetrate the atmosphere more efficiently. Daytime air temperature may range above 130 degrees F, and surface ground temperature may be considerably more. At night, heat dissipates quickly and temperatures may drop 50% or more. Winter temperatures may be freezing.

Desert soils are usually impregnated with sodium and potassium salts and other soluble minerals that cannot be efficiently leached out by infrequent rain. Plants tend to be specialized, and are mostly hard and thorny. Animals tend to burrow by day.

Australian Deserts:

Australian deserts tend to be alluvial types. That is, they have been formed primarily as a result of prevailing high-windiness which erodes and works the dry soil of the great plains. Dust is deflated, and residual sand is concentrated into dune ridges and wind-rows. Most dunes are elongated in the direction of the dominating winds, but some may be boomerang-shaped across wind. Some Australian deserts, however, are stony, formed of gibbers and other varieties of "lag" gravels. Sturt's Stony Desert about north-eastern South Australia is a particularly good example of this.

Australia's enormous deserts are now fixed, or in a delicate balance. Sand tends to "move" predominantly along the "live" dune crests. It is now believed that these dune systems are largely sub-fossil. They are relics of the Pleistocene Ice Age. At that time Australia was much windier, due to more intense cyclonic winds then impinging on the continent. These gave an over-all subcircular dune pattern about central Australia, one that is actually "anticyclonic" in circulatory direction. Prevailing winds blowing in excess of 15 to 20 miles per hour for long periods were largely responsible. Westerly winds influence dominated across South Australia (from Perth to Tasmania), becoming south-westerlies then southerlies swinging to south-easterlies in central New South Wales, and easterlies back across central-northern Australia.

Recent studies have shown that this wind system was much more intense than modern winds, and that modern dominating winds are at variance, particularly in the south, where cross winds are actually destroying the earlier impressed patterns.

That drought is not an essential feature of longitudinal sand dune formation is readily appreciable in northern Tasmania and on Cape York Peninsula, Queensland. Here enormous dunes are extending away from the coast in wet climates, and forcibly enough to overwhelm even dense "jungle".

Another feature of Australia is the predominant red colour away from the washing action of our few internal "rivers". Iron oxide accumulates as microscopic layers around each quartz grain. This is the same basic ingredient as in rouge.

Lunettes, the peculiar subcircular lakes spread widely across Australia, are also a fossil desert phenomena. They are characterized by lunar shape and lunar-shaped sediment mounds on one side - and this lies on the downwind direction of the deserts even though these directions may not coincide with modern prevailing winds. It seems that lakes in the Ice Age may have dried out periodically even despite the higher rainfall than today, and gypseus and clayey dusts blown from the dry lake beds were entrapped downwind by vegetation.

As further evidence of the erosive power of the "subfossil" glacial phase winds, prolonged dust storms were the order of the day. Where these dusts settled out, layers of loess-like (extremely fine-grained) "parna" accumulated. Successive new fossil soils became interleaved between alluvial soils of the less windy intervals as the plains were built up.

Semi-deserts surround the central cores of Australian deserts, and, in these, concentric patterns of lag gravels reveal local soil instability. Usually these patterns develop on very low slopes and the secondary sub-circular and concentric low ridges became separated by swampy depressions and crab holes left as the stony soil creeps by gravity.

Although deserts are usually conspicuously sands, ridges of crystal seed gypsum, and particularly of flour gypsum, may also appear prominently. These are mostly associated with emphemeral dry "lakes" of terminal internal drainage systems. The lighter saline residuals (salt and potash minerals) are mostly deflated (blown away) by persistent windiness, concentrating the coarser gypsum into mounds and eventually spilling over into downwind dunes. It is not an unfamiliar sight even now to experience "white-outs" during windy days due to salt dust deflation from dry lake surfaces. Most of this salt eventually gets blown out to sea via north western Australia. This is why central Australia, despite its almost complete internal drainage of saline surface waters, is not the repository of great salt lakes. Lake Eyre alone is notable for salt deposits but its accumulations rarely exceed about one foot in thickness and then only in the southern limits. Salt lakes to the south owe their accumulation more to persistent supply from coastal surf and windborne dust, or to the cutting-off of arms of the sea.

The Simpson is probably the most formidable of the Australian deserts. Individual dunes may persist practically unbroken for hundreds of miles. These may be 50 to 100 feet high and generally they are asymmetrical in cross section. Gentle slopes occur on the west, whereas the east slopes are generally live-sand avalanche faces. In consequence of this, desert operators find westward travel far more difficult than easterly.

Minor sand structures include beautiful sand rippling and coarsely avalanched cross-bedding. Sand surfaces are usually crossed with mazes of animal tracks left during quiescent wind periods. Lizards choose to burrow into the soil on the downwind side of vegetation clumps where their holes are more protected from drift.

The sands of the dunes are remarkably even grained, and grain size averages about three-fifths of a millimetre in diameter. Sands in the interdune or corridor "flats", however, are mixed in nature. Frequently, two dominating sand grain sizes inter-mingle, the grain size of the coarser sand approximating ten times that of the finer. This results in a grain locking that tends to stabilize the interdune floors.

Desert Oddities:

It was coincidence that a great shower of meteoric black glass fell during the latest desert phase. This material from outer space constituted australites, which have characteristic dub-bell, tear-drop, pudding-stone and flanged-button type shapes developed in their fiery passage through the upper atmosphere. Erosion of alluvial soils down to their clay-subsoil horizons produced the familiar clay-pan scalds on which these australites became concentrated in considerable numbers. Aborigines frequently aided the process of concentration by collecting them and leaving them in favourite spots where they camped or patiently chipped their spearheads.

An oddity of desert prevailing wind action is the angular pebbles called "driekanter" pebbles. These triangular or other polygonally facetted stones are believed to have been eroded by sand blast as they rolled over, enabling new faces to be presented to wind erosion.

Still another feature of deserts is the phenomenon of desert polish. Silica or oxidized iron and manganese impregnate surfaces of rocks and present a thin skin of high polish. This is so-called desert varnish.

Desert Riches:

The hot arid areas of the world mostly lie at low elevation in relation to sea-level. For this reason they are the land areas most likely to be invaded by the sea down through geological history. Inland seas in turn are favourable places for oil and gas generation and eventual accumulation if enough sediments are deposited. Much of the world's petroleum, in consequence, is found in these areas.

High summer evaporation and low annual rainfall also bring their own harvest. Salt, potash, gypsum, borax and lithia are particularly valuable "evaporite" deposits, and most of the worlds commercial resources of these minerals are locked up in deserts of their fossil deposits.

Sunshine is, of course, the greatest of all desert resources. Travellers may curse it, and the old prospector frequently died by it, but sunshine is the basic element of all life as we know it - along with water and air. Plant growth can only occur in sunlight, and given the other favourable conditions it is true that the more sunlight the more plant growth. This, then, raises the earliest quoted truism that deserts harbour the greatest world land bank now remaining to be tapped - almost eight million square miles of it. Certainly, the problems that go with them are formidable, but the challenge for man remains. Science and engineering will increasingly work miracles in these vastnesses.

Irrigation will continue to divert tropical run-off waters into these parched areas. Artesian water basins will be used more efficiently, but it is to the purification of seawater and other saline water sources that man looks with greatest hope. Energy requirements will come eventually mostly from atomic sources, but solar energy will play its part - and there is plenty of sun energy about deserts.

Australia, for its part, is particularly fortunate in that most of its deserts cover widespread artesian basins. These include the Great Artesian Basin, the Canning Basin, the Gibson and Victoria Desert Basins, and, "marginally", also the Murravian and Georgina "semi-desert" Basins.

Even at this time salt, gypsum and anhydrite in sedimentary deposits from past eras are being cut by oil drilling rigs in desert places. These are being found as far away as the Canning Desert. Geologists have great hopes that potash and sulphur will also be found. Truly, deserts will yet be found to harbour some of Australia's greatest resources.

The official emblem of the Commonwealth Bureau of Meteorology.

The emblem is a stylised representation of the southern hemisphere tropical cyclone with clockwise winds spiralling inwards to the calm, cloudless "eye" at its low pressure centre. It may also be interpreted as the outwards anticlockwise spiral of winds from an anticyclone, or "high." To some it may suggest the role of the sun's energy in powering the atmospheric engine.

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